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Manufacturing Technology Information Analysis Center

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MTIAC SOAR-88-03

VISION TECHNOLOGY FOR AUTOMATED INSPECTION OF HYBRID MICROELECTRONICS ASSEMBLIES

June 1988

Therese M. Philippi
IIT Research Institute

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Prepared By:
Cresap, a Towers Perrin Company
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A Department of Defense Information Analysis Center

Overview

MTIAC is a Department of Defense (DoD) Information Analysis Center. MTIAC serves as a central source for currently available and readily usable data and information concerning manufacturing technology. The primary focus of the Center is to collect, analyze, and disseminate manufacturing technology for the production of defense materials and systems.

The funding agency for MTIAC is the Defense Technical Information Center of the Defense Logistics Agency of the Department of Defense, in Alexandria, Virginia. MTIAC's data collection and dissemination function is tied to DTIC by a shared bibliographic data base.

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MTIAC also serves the civil sector within the constraints of the priorities of defense needs and limits on disseminating information, because of security classification, and the export laws and regulations on technology transfer.

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- Maintains a DoD Manufacturing Technology Program (MTP) data base
- Prepares and publishes handbooks, data books, reference works, state-of-the-art reviews (SOARs), critical reviews and technology assessments, conference proceedings, newsletters, and other publications
- Responds to technical, bibliographic, and other user inquiries
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- Performs special tasks for government users, separately funded through the MTIAC contract.

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The purpose of this review is to determine what is currently considered state-of-the-art for visually inspecting hybrid microelectronic circuits during assembly, with particular emphasis on the use of automation. In order to understand the feasibility and extent to which automated inspection equipment could be implemented, consideration has been given to the following: (1) the hybrid circuit industry in terms of its structure and market significance, (2) the process stages where visual inspection is needed, and (3) the various forms of visual inspection in use and development, including optical microscopy, 2-D, and 3-D machine vision.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF EXHIBITS

EXECUTIVE SUMMARY

The purpose of this review is to determine what is currently considered state-of-the-art for visually inspecting hybrid microelectronic circuits during assembly, with particular emphasis on the use of automation. In order to understand the feasibility and extent to which automated inspection equipment could be implemented, consideration has been given to the following: (1) the hybrid circuit industry in terms of its structure and market significance, (2) the process stages where visual inspection is needed, and (3) the various forms of visual inspection in use and development, including optical microscopy, 2-D, and 3-D machine vision.

The primary focus of this study is hybrid circuits used in defense systems. Consideration has been given to the nonmilitary sector in terms of how the hybrid industry could support and contribute to the state-of-the-art. This review considers both thick- and thin-film hybrids, but excludes microwave devices.

Hybrid Industry

There are an estimated 1500 U.S. companies which can produce hybrid microelectronic circuits. Of these, approximately 30 percent or 450 companies produce in excess of $2 million worth of hybrids per year. Two important factors should be noted. One, these are not necessarily small companies, but may be large companies for whom hybrid production is a small portion of their activity. Secondly, a large amount of hybrids are made for captive usage. Military usage of hybrid circuits accounts for 20 to 30 percent of the dollar value of the U.S. market and approximately 15 percent of the world market.

Visual Inspection

Visual inspection is used at five stages of the hybrid assembly process: incoming components, substrate screening, component and die placement and attachment, wire bonding, and pre-cap.

Optical microscopy is considered the state-of-the-art inspection technique and is used by virtually every producer of hybrid circuits at some stage of the process. Research and development in optical microscopy is limited to incremental improvements.

Most two-dimensional machine vision systems were developed for printed circuit board inspection and have been adapted to hybrid production to inspect substrates. Of the five stages, substrate screening is distinct because it can be done using two-dimensional machine vision. Several companies currently make equipment for this purpose. The other four stages require three-dimensional inspection.

Three-dimensional machine vision represents both the greatest challenge and the greatest opportunity in automating hybrid inspection. There are seven companies actively pursuing the development of 3-D systems for microelectronics inspection. Present 3-D systems are used for inspecting solder joints, wire bonds, and pre-reflow solder inspection.

Automated vision systems have two main components: image acquisition and the computational aspect. Sensors and illumination techniques are the focus of research for image acquisition. Illumination is particularly important to achieving 3-D. Structured lighting with fiber-optics is a predominating approach.

In the computational aspect, the major trends and developments are in optical computing, gray-scale and color image analysis, pattern recognition, artificial intelligence, and computer architecture.

The use of optical computing for image system processing is in the research stage. It would be used to preprocess the analog signal before conversion to a digital signal. The purpose of preprocessing is to separate and distinguish the image from background "noise".

Gray-scale and color refer to how an image is represented within the computer. The major advances in gray-scale image analysis are larger arrays, resulting in greater resolution. Color image analysis is useful for recognizing color-coded parts, fiducials, and components doped with a colored material. Material trends, multilayer ceramics, and finer geometries are the factors which will decide whether gray-scale or color predominates.

In pattern recognition, an object or feature within an image is represented as a set of numbers and assigned to a known class of similar objects. There are three steps: segmentation, feature extraction, and classification.

Pattern recognition is algorithmic. It calculates and classifies features of the image and determines if that feature is within allowable relationships.

Pattern recognition is an area where considerable improvements can be foreseen. Most present machine vision systems are based on a few vision algorithms from the last decade. Newer techniques are under development, particularly in segmentation, edge detection, and feature extraction.

Image processing systems are also trying to make use of artificial intelligence, especially expert systems. There are two factors to note. First, those that use heuristic searching do not always result in the best solution, but rather one that is "good enough" within its limitation. Secondly, expert systems are highly dependent on the knowledge base. Establishing expert criteria can be a significant problem for some inspection tasks.

Computer architecture is also significantly improving automated vision systems. Parallel processing through pipelined systems and systolic arrays are resulting in higher throughput and lower cost for processing larger quantities of data.

Conclusions

In conducting this review, the following questions have been addressed:

- Is there a need and willingness for automating hybrid circuit inspection?
- What are the advantages of an automated vision system over human operators?
- What are the limitations of machine vision systems?
- At what stage should automation be introduced?
- What opportunity does the hybrid industry represent to machine vision producers?
- What are the implications of automating inspection to the U.S. hybrid circuit industry?

Need and Willingness

The hybrid industry is somewhat unique in its willingness to adopt new technology. Automated production is becoming increasingly prevalent in hybrid assembly, especially wire bonding and substrate screening. Most major producers have considered automating inspection and many have tried to implement it. In a sense, automation represents an antithesis for hybrid inspection.

Automated production creates a greater need for automated inspection as an integral part of the assembly process. However, present inspection systems cannot keep pace with automated processes.

Machine Vision or Human Inspectors

The principal factors affecting the choice between machine vision and human operators are economics, subjectivity, information management, and facility usage. At face value, automated inspection systems are expensive compared to using human operators and optical microscopes. However, there are other factors to consider. Foremost is the need to reduce the ambiguity associated with human inspectors. At present, inspection is very subjective and highly operator-dependent. Machine vision systems apply the same criteria to each inspection and can remember it as well. Information management is another advantage of automated machine vision systems. Since the information is already in a digital format, it can easily be archived for future reference, analyzed for optimizing process control, or incorporated to directly feed back to rework or a production station. Better use of production floor space may be another advantage.

Limitations of Machine Vision Systems

There are several limitations and criticisms of existing machine vision systems. Among them are sensitivity, template matching, throughput, and signal processing. Sensitivity is a major problem. Most users cannot find a compromise between false alarms and false pass. Template matching requires a perfect part which is another problem. Throughput is a trade-off with cost. A 10 percent increase in throughput could double the price of an inspection system. Signal processing is another limitation of present machine vision systems, but one that offers a significant opportunity for improvement through preprocessing, pattern recognition algorithms, and hardware.

Optical discernment is another problem often cited. However, no clear solution is seen in the near term. Setup time is also cited as a problem, but the increased implementation of CAD/CAM should reduce it as an issue.

Stage to Automate

Opinion varies widely as to what stage to automate inspection. Although it would be desirable to automate at each stage, the greatest interest seems to be at pre-cap. There are two schools of thought. One is that pre-cap is too late because all of the value-added is already in the device. The other is that pre-cap is the most useful stage to automate because it is the most labor-intensive, the most complex due to the multiplicity of components, and is required by military specifications. Also, it is felt that automating pre-cap inspection would minimize contamination.

Machine Vision Market in Hybrid Assembly

The general consensus among both hybrid circuit and vision system producers is that, at a price of $100,000 or more, the market for automated vision systems in hybrid assembly is 15 machines. However, it is anticipated that the technical developments in optics, image acquisition, and signal processing that would be incorporated into a hybrid inspection system could be further developed to serve products in larger markets.

Implications of Automating Inspection

The initial users of automated inspection equipment would be major producers of hybrids. However, the hybrid microelectronic circuit industry is unique in that the dominant producers vary from year to year based on end-use product markets, such as cellular telephones, disk drives, the demand for a particular model of an airplane, or a particular military weapon system. This fluctuation in production levels does not favor automation investment. However, automated inspection, if broad enough in its application, could stimulate greater production by independent companies to meet the specific demands those products.

The premise is that automation would ultimately improve quality and lower cost or at least maintain a competitive cost.

As in the printed circuit board industry, the successful implementation of automated inspection would most likely result in a shakeout of undercapitalized small- to medium-size producers, with certain small, specialized "niche" producers always maintaining a presence. However, this is being foreseen to some extent regardless, due to material changes, product complexity, and increasing competitive pressures, particularly as offshore producers focus more on the custom segment of the business.

1.0 INTRODUCTION

Since their mass production began in the 1960s, hybrid microelectronic circuits have remained a vital and steadfast part of the circuit industry. Basically, hybrid microelectronic circuits are a very efficient packaging technique, with the primary advantages of size, better resistance to environments, and the flexibility to intermix devices and components of different technologies on the same circuit, to achieve a common function. Hybrids have several unique characteristics compared to other circuit formats: short lead lengths, close spacing, low noise pickup, tight thermal coupling, superior stability, few connections, low weight, hermetic sealing, shock and vibration resistance, and high precision resistor values. Compared to monolithic integrated circuits, hybrid microelectronic circuits have shorter production runs, less volume per run, and require less time and cost for development.

Automated equipment has been introduced to address a variety of aspects associated with electronics production, including automatic die bonding, automatic wire bonding, and automatic component insertion. Recently, electronics automation equipment has been introduced with sophisticated vision technology as an aid in the assembly tasks. This equipment has been controlled on the basis of physical registration of parts through special marking, holes or indexing methods using more traditional sensing technology.

It is important to recognize that automation of electronics assembly has been maturing unevenly across the spectrum of electronics assembly categories and tasks which are encountered. Specifically, semiconductor production and printed circuit board assembly, which are almost at opposite ends of the electronics spectrum, have benefited from automation because of the nature of the tasks involved. In the case of semiconductor production, this includes discrete device fabrication, thick and thin film deposition, wafer fabrication and photolithography. In the case of printed circuit boards, this includes multilayer board fabrication, automated hole drilling, and automatic component insertion.

Between these two ends of the spectrum lies hybrid microelectronics. In the last five years, numerous technical developments have stimulated the advancement of machine vision systems. At the forefront of these developments is the introduction of array processors, pipelined hardware, and advancements in solid-state image sensors. Through the adaptation and implementation of these technologies, present-day vision systems have better resolution and can process larger quantities of data in more reasonable time and cost. Thus, opportunities to apply machine vision to automated assembly of hybrid microelectronic circuits have also emerged.

As in most industries, competitive pressures for higher quality, lower cost, and better performance are driving the state-of-the-art both in products and production. In particular, the products are becoming more complex which is forcing better production methods. Inspection is a vital and integral facet of the hybrid microelectronic assembly process. It is the unique characteristics of hybrids, combined with the multiplicity of devices and components which can be integrated within the same circuit format that presents such a tremendous challenge for visual inspection.

The purpose of this review is to determine what is currently considered state-of-the-art for visual inspection of hybrid microelectronic circuits during production and, in doing so, to consider the dynamics of the hybrid industry as well as the availability and development efforts associated with automated vision technology applied to hybrids for military use.

2.0 DEFINITION, SCOPE, AND OBJECTIVES

In the past few years, the term hybrid circuit has undergone an evolution of meanings. With the increasing usage of surface mount technology, the distinction between hybrid circuits and printed wiring boards is narrowing.

Some producers extend the term hybrid to include devices consisting of a variety of components which are surface mounted on a substrate and then dipped or coated with an epoxy. However, these are not usually found in the custom and military segments and, therefore, not subject to the in-depth inspection required of custom and military hybrids.

Traditionally, printed wiring boards consist of a large substrate and through-hole mounted devices, but increasingly surface mount technology is replacing through-hole.

Another recent approach is to mount hybrids on a ceramic or epoxy substrate. Although each of these approaches has commonalities, key distinctions are that hybrids are wire bonded, boards are not coated or encapsulated and, in general, boards tend to be epoxy substrates and hybrids ceramic.

In the traditional sense, and the subject of this study, a hybrid microelectronic circuit is defined as a multiplicity of discrete components assembled on a substrate using either a thick- or thin-film process, and wire bonded to achieve a given circuit function. Normally, the entire assembly is hermetically sealed and shares a common enclosure.

The primary focus of this study is vision technology applied to inspection of hybrid microelectronic circuits used in defense systems. Consideration has been given to the nonmilitary sector in terms of how the hybrid industry could support and contribute to the state-of-the-art. This review considers both thick- and thin-film hybrids, but excludes microwave devices. Information was drawn from U.S. sources and included telephone and personal interviews as well as published sources.

The study concentrates on inspection of the mechanical aspects of hybrid microelectronic assembly. The use of vision technology for controlling electrical surface characteristics or electronic testing of circuits is not within the scope of this study.

The specific objectives of this review are to:

- Provide an overview of the hybrid industry and market

- Consider currently used methods for hybrid microelectronic circuit inspection

- Consider methods in development, particularly three-dimensional machine vision.

3.0 MARKET OVERVIEW

3.1 MARKET SEGMENTATION

A convenient way to segment the hybrid microelectronic circuit industry is by the end user product. The three principal segments are commercial, custom, and military. Exhibit 1 illustrates the U.S. market share of each segment as a percentage of dollar volume.

EXHIBIT 1
U.S. MARKET SHARE, BY SEGMENT
(percentage of dollar volume)

Commercial	25 to 35%
Custom	40 to 60%
Military	20 to 30%

3.1.1 Commercial Segment

In terms of numbers of circuits produced, over 50 percent of U.S. production is in the commercial sector, as is most of the offshore production. Important markets for commercial producers include computers, especially disk-drives, television, audio equipment, watches, toys and games, motor vehicles, and consumer medical products such as blood pressure devices and glucose monitors. Commercial hybrids typically cost less than $15.

Characteristically, these circuits are low-cost, high-volume, mass-produced. They operate in the 0° to 70°C range. There is usually a limited number of designs, but each is produced in high volumes. The production process incorporates automation and requires less process steps than military or custom circuits. Inspection is on a random sampling basis, with the emphasis being on electrical and functional testing. Process control is critical and the focus of most R&D efforts. The philosophy of commercial hybrid circuit producers is that you cannot inspect a problem away, and good process control produces good quality.

3.1.2 Custom Segment

Custom hybrid circuit producers can be viewed in three categories: those having annual sales of less than $2 million, annual sales of $2 million to $5 million, and greater than $5 million in annual sales.

The custom hybrid business, as its name implies, functions to respond to a customer's special and specific needs. Producers doing less than $2 million per year will typically make only a few types of circuits, such as amplifiers or transmitters. Since they have such low volumes, they usually do 100 percent inspection at all five stages using optical microscopy. It is unlikely that hybrid producers doing less than $2 million in annual sales would implement automated inspection equipment and they are not a principal focus of this study.

Of greater interest is the custom producer doing greater than $2 million, and probably more than $5 million per year in sales of hybrid circuits. The primary applications of custom hybrid circuits are avionics, particularly black box systems; telecommunications, especially switching; medical devices for critical applications such as pacemakers; and scientific and engineering instrumentation. In the custom segment of the hybrid circuit business, there is a large percentage of captive producers. Perhaps this is a reflection of the high liability risk associated with many of their primary applications.

Another characteristic of the custom segment is a high number of active designs. Most companies have, at any given time, 500 active designs, but the number may be as high as 1000. Production runs of a single circuit design would be at least 100, with 100 to 1000 being common. However, a major custom house may do 7000 to 8000 per month of a design with an annual output of 30,000 circuits of one design. Custom hybrids typically cost in the $15 to $500 range.

3.1.3 Military Segment

The military segment of the hybrid circuit business is unique in that it operates in a manner similar to a regulated business. Microelectronic devices suitable for use within military and aerospace electronic systems must be produced within the standards established in Military Standard 883-C.

Certification requirements for hybrid microcircuit facilities and lines are established in Military Standard 1772A.

In 1982, the Defense Electronic Supply Center (DESC) was requested to administer the custom hybrid certification/qualification program as an agent for Rome Air Development Center. Certification/qualification is process-specific within a company or facility. Any major process changes or new processes would require new certification.

Certification is limited to companies which produce onshore, in U.S. territories, or a company whose government has a special reciprocal agreement with the United States Government. Whether or not a hybrid circuit used for military purposes must be produced in a certified/qualified facility is specified within the procurement contract. Prior to November 29, 1986, contracts may have simply said to build to Military Standard 883-C, but since that date hybrids are purchased from a certified producer whenever possible. There are some exceptions, but certified producers are preferred and will become more so. Military Standard 454 serves as a guideline for order of precedence. Exhibit 2 is a flow chart of the qualification process. At present, only 17 companies have qualified and another 50 are at various stages of the process. However, over 200 companies have requested application information.[1]

This illustrates the importance of the military market in that nearly half of the U.S. hybrid producers doing greater than $2 million per year are interested in military certification. The principal attraction to this market would appear to be the high value-added per circuit. The cost of a hybrid circuit used in a military system is typically $500 or higher. For thick-film hybrids, material costs are estimated at 50 percent and the testing, inspection, labor and related assembly costs are 50 percent. For thin-film hybrids, materials represent approximately 25 percent of the cost and the testing, inspection, labor and related assembly costs are 75 percent.

Inherently, circuits produced for the military are much more complex and have more stringent performance requirements, particularly in their resistance to environments and need for high reliability.

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[1]Defense Electronics Supply Center, Dayton, Ohio.

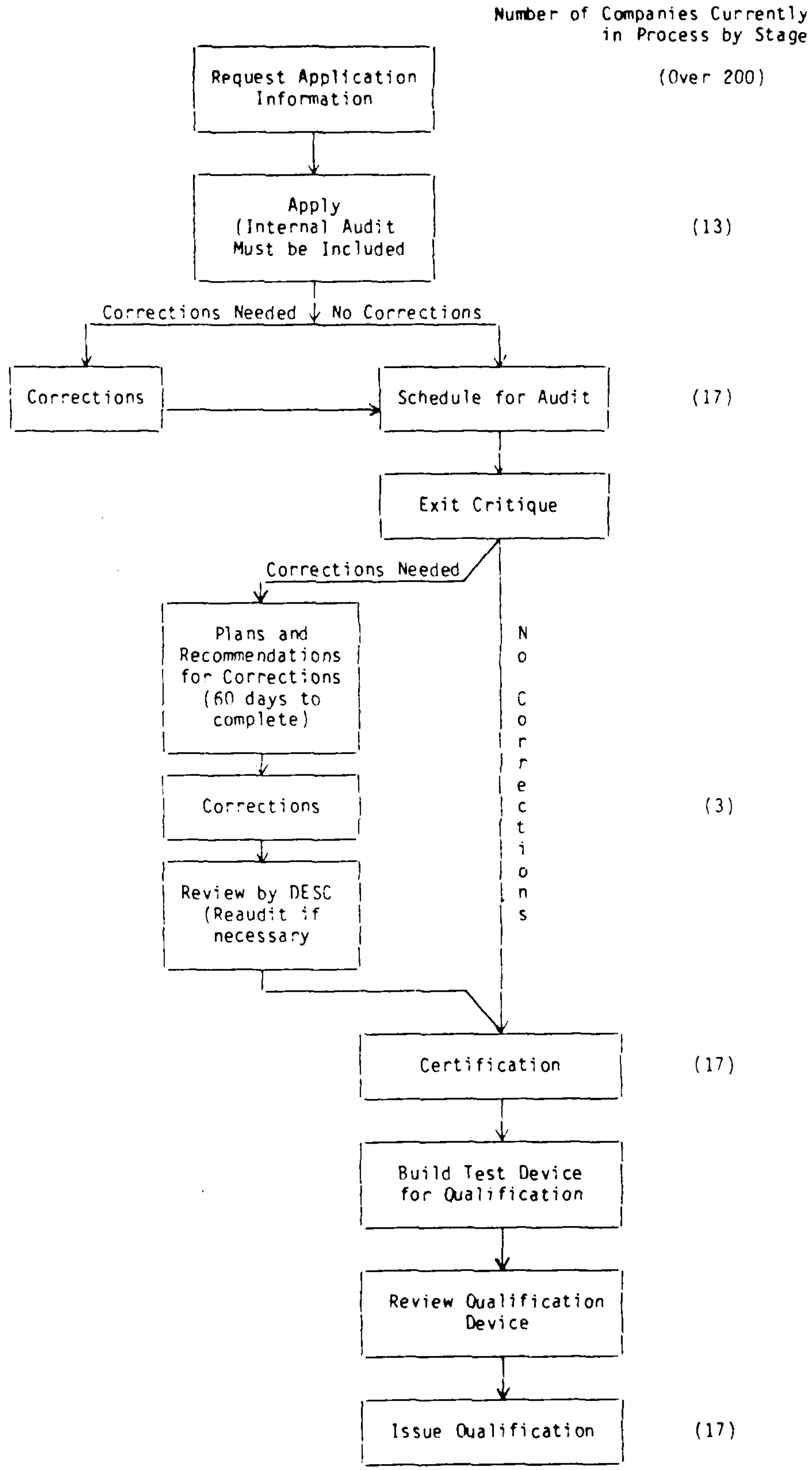

Exhibit 2
D.E.S.C. Hybrid Production Certification Process

3.2 MARKET SIZE

In 1984, an input-output analysis estimated U.S. production of thick-film hybrid circuits at $4.4 billion.[2] Assuming that 85 percent of circuit production is thick film and 15 percent thin film, the total value is $5.2 billion. In the 1984-85 period, semiconductors are assumed to have remained near constant. The 1985-86 growth rate for the SIC category 3674, Semiconductor and Related Devices, which includes hybrids, was 5 percent, resulting in a 1986 U.S. production value of $5.4 billion.[3]

Exhibit 3 shows the 1986 world production of hybrid microelectronic circuits to be approximately $8.9 billion. Assuming U.S. military usage to be 25 percent of U.S. production, hybrid circuit production for U.S. military and aerospace electronic systems would account for 15 percent of the value of total world production.

EXHIBIT 3
ESTIMATED 1986 WORLD PRODUCTION OF HYBRID MICROELECTRONIC CIRCUITS

Producer	Value (millions)
United States	$5,400
Japan*	994
Western Europe	1,290
Other Pacific Rim	1,200
	$8,884

*Japanese Ministry of International Trade and Industry.

Excluding the military segment, the United States accounts for 54 percent of the value of world production. The next largest single producer is Japan which accounts for 13 percent. Exhibit 4 illustrates key segments and the respective percentages each represents of U.S. production and of Japan's

[2] Semiconductor International, 1984.

[3] U.S. Department of Commerce.

production. The largest application is computers, which includes office automation, communications and entertainment. Motor vehicles and medical are smaller percentages, but represent important growth areas.

EXHIBIT 4
MARKET SEGMENTS, U.S. AND JAPAN, 1985
(percentages are of production value)

Segment	U.S.	Japan	Combined Portion of World
Communications	20%	14%	10.5%
Computers (including terminals)	25%	12%	12.6%
Entertainment	12%	28%	8.2%
Motor Vehicles	8%	19%	5.5%
Medical	7%	--	3.2%
Other	28%	27%*	--
	100%	100%	

*Industrial 22%
Consumer 5%

3.2.1 Communications/Computers/Entertainment

Combined, these three categories account for nearly one-third of world usage of hybrids. The U.S. predominates in computer and communication usage of hybrids, while Japan dominates the entertainment segment. Common uses of hybrids include television, VCR, radio, cable television, disk drives, modems and telephones, especially cellular phones. The major trends are to more digital, high frequency and radio frequency products. Major producers include Motorola, IBM, and AT&T.

3.2.2 Motor Vehicles

This segment of the market is a significant growth area for hybrid microelectronic circuits. In 1985 hybrids produced in the United States and Japan for use in motor vehicles represented $309 million and $156 million, respectively, or 5.5 percent of the world market. Other major producers of hybrid circuits for motor vehicles include: Hong Kong, Singapore, Korea, and Malaysia.

In 1987, the U.S. alone produced 7.3 million passenger cars and 3.8 million trucks. It is estimated that the average vehicle contains seven or eight hybrid circuits, making the 1987 usage in U.S. motor vehicles between 75 million and 90 million circuits. The price per circuit ranges from $1 to $15 with the average being less than $5. Environmental control sensors cost approximately $50. The types of products currently using hybrids include radios and instrumentation panels, illumination, ignition modules, and voltage regulators.

The quantity of electronics in motor vehicles is expected to increase dramatically. In 1986, the average passenger car contained $350 in electronic parts. By 1990, that is expected to increase to 12 percent of the cost of the car or $1,440. The types of devices include the following:

- electronically-controlled adjustable suspension
- computer-controlled transmission
- computer-controlled steering
- electronic fuel injection
- climate control
- electronic anti-skid controls
- heads-up displays.

Presently, most electronics are inside a car or in the trunk. With the trend to reduce size, weight, and cost, there will be an increased use of electronics under the hood. This will also increase the use of hybrids rather than printed circuit boards, particularly because of the need to protect circuits from a hostile environment such as salt, heat, and moisture.

Included among the major U.S. producers of hybrid circuits for motor vehicles are:

- o Delco (General Motors)
- o Ford
- o Automotive Controls
- o Borg-Warner
- o Chrysler

3.2.3 Medical

The medical market for hybrid circuits is characterized by two types of products. One is the low-cost, mass-produced commercial segment. Typically, these cost $1 to $2. Major products using hybrids include pressure transducers for blood pressure monitors and glucose monitors. In 1985, there were 2.5 million blood pressure devices made in the U.S. alone.

At the other end of the spectrum are custom circuits used in critical products such as pacemakers and defibrillators. Together, these two products use approximately 100,000 circuits per year. Other uses of hybrids in medical products include diffusion pumps, implantable drug delivery systems and hearing aids. Hearing aids are somewhat of an exception. They are an emerging application and use a noise blocker circuit which will cost approximately $35 each.

It is estimated that approximately 240 companies presently consider themselves producers for this market. Of these, 70 are really viable in that they can take on any design. Of these, there are 12 major producers of hybrid circuits for the medical industry.

3.3 UNITED STATES - INDUSTRY OVERVIEW

In the U.S., there are an estimated 1500 companies which can produce hybrid microelectronic circuits. Of these, approximately 30 percent or 450 companies are estimated to annually produce hybrid circuits having a value in excess of $2 million. It should be noted that many companies may be large producers of other types of semiconductors or electronic systems, but hybrid circuit production is only a small portion of their activity.

There is a distinct similarity between the size structure of printed circuit board companies and the hybrid industry. In 1986, approximately 45 percent of U.S. printed circuit board producers had annual sales greater than $2 million and less than 25 percent had sales of greater than $5 million.[4]

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[4]Derived from data source: Electronic Business, September 1, 1987, pp 78-80.

The business of producing custom hybrid circuits has a relatively low barrier to entry in terms of initial capital cost. However, there are considerable barriers to being a medium- to high-volume producer. The foremost is the high cost of automated capital equipment and, correspondingly, the ability to incorporate it into the production flow. Another is the ability to do production runs in response to customer needs. In custom work, the quantities a customer needs of a single design may be sporadic, ranging from 100 one month to 2000 the next. Lead times and response times are very important to the hybrid business.

One example which illustrates both these barriers is computer-aided design (CAD) capability. The ability to design a hybrid circuit using CAD, store that design, and go directly to production from CAD, represents a clear advantage in both cost and response time. However, a considerable volume of production and number of designs is required to make the investment economical.

Exhibit 5 illustrates typical price ranges for optical equipment used in electronic assembly inspection. This is useful in considering the sales volume required to make an automated inspection system affordable. An automated optical system in the $50,000 to $75,000 price range would be between 2 and 4 percent of annual sales for a company doing $2 million in sales, which is probably an upper limit for investment.

EXHIBIT 5
PRICE RANGE OF OPTICAL CAPITAL EQUIPMENT
FOR ELECTRONICS ASSEMBLY INSPECTION

System Type	Price Range
Manual system	$15,000 to $20,000
Automated system	$50,000 to $75,000
Critical measurement system	$70,000 to $200,000
Multistep systems	$100,000 plus

3.4 JAPAN - INDUSTRY OVERVIEW

Over 200 companies in Japan manufacture hybrid integrated circuits. In 1986, total hybrid production is estimated to be 169.0 billion yen or $994 million. This was a 2.8 percent increase from 164.4 billion yen in 1985. Hybrid production accounted for 22 percent of the combined hybrid and discrete semiconductor production. The Japanese Ministry of Trade and Industry estimated the average price of a hybrid in 1985 to be 457 yen or $2.29. Approximately 95 percent of hybrids produced are thick-film and used in commodity products. Shinzaburo Kamei of Matsushita Electronics Corp. sees future hybrid products as polarizing into two areas: high-performance, high value-added products and low-priced, miniaturized devices. Thin-film hybrids are expected to increase and custom hybrids are anticipated to have a high production share.

Among those companies prominent in the Japanese hybrid industry are:

NEC
TDK
Fujitsu Ltd.
Hitachi
Matsushita Electronic Components
Sanyo Electric
Murata Manufacturing
Mitsumi Electric
Sanken Electric
Tokyo Electron
Nippon Chemi-Con
Sumitomo Metal Mining

It is interesting to note that Japanese hybrid producers include not only electronics companies, but chemical and mineral producers as well, indicating forward integration by some suppliers. Also, as in the U.S., there is a considerable amount of captive production.

4.0 CURRENTLY USED METHODS

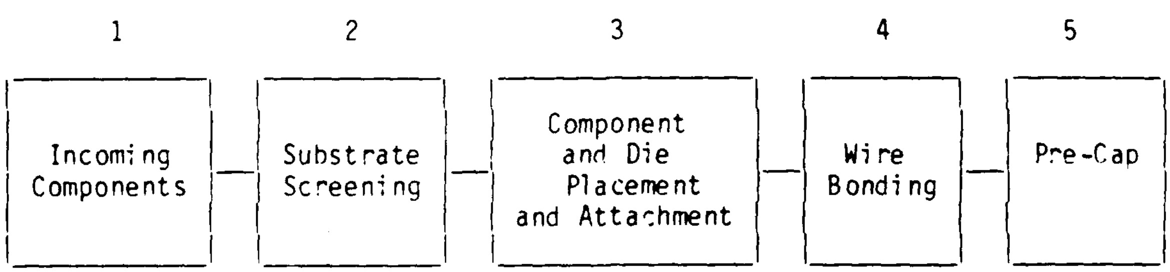
In considering the methods used for visual inspection, it is important to also consider the organizational structure in which inspection is done and the basic process steps which require visual inspection.

4.1 TYPES OF INSPECTORS

There are two types of inspectors: quality control people and inspectors who are an active part of the manufacturing floor process. In some cases, there is a third type--government inspectors. Quality control inspectors are usually responsible for incoming components and final product before shipment. The in-process inspection is done by assembly inspectors. This presents an interesting situation. Within the organizational structure of most hybrid producers, quality control and manufacturing operations are distinctive of one another. In some companies, incoming components and in-process inspection are both under quality control; however, each is still done by different people with distinct functions. Therefore, each has a different approach and perspective to inspection. Understanding the needs and problems of manufacturing assembly by quality control and communication between the two groups is extremely important.

4.2 BASIC PROCESS STEPS AND VISUAL INSPECTION NEEDS

The basic process stages of hybrid circuit assembly where visual inspection is a key factor are as follows in their order of occurrence:



4.2.1 Incoming Components

The inspection of incoming components is not considered part of assembly and is generally under the realm of quality control. At this process stage, components are received, inspected, and assembled for production into either a waffle pack or mylar aperture cards. In some cases, 100 percent inspection will be done, but more often a random sampling is taken and examined for gross defects. The inspection emphasis at this stage is on element analysis, "infant mortality", and electrical integrity. Handling is an important aspect at this stage.

4.2.2 Substrate Screening

Inspection at this stage primarily looks at patterns, ensures that there are no shorts, that the proper screen was used and paste is in the proper place and in an appropriate quantity. Other defects to look for include chipouts, cracks, holes which are not part of the design, pits, scratches and line cuts.

Substrate inspection is primarily a two-dimensional problem.

4.2.3 Component and Die Placement and Attachment

The steps done at this inspection include die-bonding, solder paste or epoxy dispensing, if it has not already been applied at the screen printing stage, component and lead attachment, reflow soldering, and cleaning.

The main things one looks for at this inspection stage are orientation and alignment, to verify if the right part is present, and to measure die size. Inspection at this stage is especially important to Class S producers because they are limited to only two reworks. If the wrong die is present and bonded, removal may be difficult at a later stage.

4.2.4 Wire Bonding

The purpose of wire bonding is to form an interconnection between a die and the substrate or the substrate and the package lead frames. Wire bonded dies are usually integrated circuits, but they could be other types of components as well, such as transistors, diodes, or even discrete resistors. The standard number of wires is 300, but a complex chip could have as many as

2000. The trend is to higher chip counts per circuit and higher chip density, making wire bond inspection an even more difficult problem that it already is.

Wire bonds are frequently referred to by their two basic shapes which are ball bonds and wedge bonds. The shape of the bond is dependent on the technique used, the material, and its sensitivity to temperature. The most common wire material used is gold or aluminum. However, aluminum wire is usually doped with a hardening material such as silicon or magnesium.

Wire bond inspection is extremely important. It is estimated that wire bond problems account for 50 percent of failed circuits. However, failure is not necessarily due to the wire bond process itself, but may be the result of handling, contaminated materials, the bond pad, variation in package type, contaminated hardware, or even the wafer fabrication workmanship.

In general, the visual inspection of wire bonds involves the following:

- Verify if the right part is present
- Verify if the part is in the correct orientation
- Trace the wire and measure the loop height (this is the height above the die rather than the substrate)
- Determine if the wire is above the edge of the die
- Verify that wires do not cross and that there is sufficient separation between wires
- Ensure there are no missing or broken wires
- Assess the appropriateness of the size of the bond in relation to the wire diameter
- Determine the location of the bond on the pad itself, especially to verify that it is entirely on the pad.

Specific causes of wire bond defects include:

- lack of adhesion
- wire lifting
- contamination
- tools scraping the surface
- stage movement or other vibration
- tool bounce
- smeared metallization
- impure material
- insufficient force (for wedge bonds)

- for ball bonds, capillary contamination
- for wedge bonds, feedhole contamination
- poor wafer fabrication, although this is much less of a problem with single source suppliers, particularly captive producers.

Among the reasons wire bond inspection is difficult are the multiplicity of die height, the multiplicity of metallization qualities, and the increasing complexity in numbers of wires per chip. The trend to new and varied materials is creating a contrast problem for visual inspection. Another problem which is exacerbated by the increased number of wires is wire diameter, wire position, and wire spacing, particularly at corners of the die.

4.2.5 Pre-Cap

Also referred to as pre-seal, this is the stage of assembly just prior to capping or encapsulating the device. This is the last opportunity to visually inspect the circuit before sealing. Hybrid circuits produced for use in military electronics systems must be 100 percent inspected at this stage according to Method 2017 of Military Standard 883C. This inspection would include all previous inspection criteria plus an examination of any additional defects, particularly those resulting from mishandling, contamination, or process problems. It is especially important at pre-cap to have good depth of field because of the multiplicity of parts present. In high-volume houses, a skilled and experienced operator will typically require 7 to 24 minutes to perform pre-cap inspection using an optical microscope.

4.3 INSPECTION

The three forms of visual inspection used in hybrid circuit assembly are human operators using optical microscopes, two-dimensional automated machine vision systems, and three-dimensional automated machine vision systems.

4.3.1 Optical Microscopy

Optical microscopic inspection by human operators is considered state-of-the-art and is used by virtually every producer of hybrid circuits at some stage of the process. Stereo microscopes and general purpose compound scopes fitted with achromatic or apochromatic objectives are the most commonly used types. For discerning questionable observations or for special applications, such as an unusual material, a different type of scope such as interference, phase-contrast, or polarized light might be used.

The magnifications used vary from 10X to 60X. Military specifications require wire bonds to be examined between 30X and 40X. Therefore, most companies doing military and custom work will inspect at 30X or 40X to avoid changing magnifications and refocusing. Depending on the volume to be handled, an operator will either have multiple objectives at his or her own station or have to physically move to another microscope to look at something at higher powers. Light sources are another important factor. Most scopes are equipped with a bright field illumination from either a white light source or directed fibers. An optional feature would be the ability to switch to dark-field illumination.

Optical microscopes also have a variety of options that are particularly useful for hybrid circuit inspection. One of these is variable stages. Microscope stages are typically adjustable in the x-y direction. However, some are also available with tiltable stages, stages which can be rotated 360 degrees, and stages which move automatically either by a preprogrammed time sequence or foot pedals. Viewing apparatus is another important feature. As an alternative to traditional eyepieces, many companies now offer viewing ports.

The key factors in selecting an optical microscope for hybrid circuit inspection are working distance, resolution, contrast, and field of view. In hybrid circuit inspection, it is usually desirable to have a long working distance because of the different heights of features on the circuit. However, there is a trade-off between working distance and resolution. Resolution is a function of the wavelength of light and the numerical aperture. Increasing the working distance usually requires reducing the numerical aperture and increasing illumination. Therefore, as a rule, a system strives for the minimum working distance necessary to maintain higher resolution.

Contrast is a major factor in hybrid circuit inspection because the variety of materials present causes varied reflectivity. The problem of reflectivity can be overcome by using various contrasting techniques and varied illumination. These include filters, dark-field condensers, polarizers, phase condensers, and phase objectives. Illumination sources include tungsten, incandescent, or quartz iodide lamps, xenon or metal-halide lamps, and directed fiber sources.

There are numerous companies supplying optical microscopes to the hybrid microelectronics industry. The following are among the more predominant.

Bausch & Lomb
Rochester, NY

Buehler, Ltd.
Lake Bluff, IL.

E. Leitz, Inc. (Wild Instruments)
Rockleigh, NJ

Mitutoyo (MTI) Corp.
Paramus, NJ

Nikon, Inc.
Garden City, NY

Olympus Corp.
New Hyde Park, NY

Reichert-Jung, Inc. (Cambridge Instruments)
Buffalo, NY

Unitron, Inc.
Plainview, NY

Vision Engineering, Inc.
New Milford, CT

Carl Zeiss, Inc.
Thornwood, NY

4.3.2 Automated Vision Systems - General Considerations

An automated vision system has two main components: image acquisition and the computational aspect.

4.3.2.1 Image Acquisition

Image acquisition involves the conversion of an optical image to a video signal and the storage of those signals. Two important features which distinguish image acquisition systems are the camera used and the approach to illumination.

Early machine vision systems used vidicons which are a light-sensitive, table-type camera. Newer systems use solid-state cameras which include line-scan and area-scan cameras. Line-scan cameras produce one-dimensional information from a single row of image sensor elements or photosites. Their primary advantage is high pixel (or picture element) density and high resolution. Because of the high pixel density and high pixel transfer rate, these types of systems usually compress the data before processing. A major disadvantage is that line-scan cameras do not allow direct display on a video monitor. Line-scan cameras are particularly useful for noncontact measurement, velocity measurement, shape recognition, and optical character recognition as in document scanning and facsimile.

Area-scan cameras are also referred to as solid-state matrix cameras because their image sensors are arranged in a matrix of rows and columns producing two-dimensional images. There are several types of solid-state array cameras including those based on charge coupled devices (CCD), charge injection devices (CID), MOS sensors, or a photodiode matrix. In addition to their two-dimensionality, they also have the advantages of low power consumption, less time to capture an image, and can be directly interfaced to a video monitor. A distinct disadvantage is lower resolution. Area-scan cameras are particularly useful in industrial environments and for machine vision systems.

In considering illumination for machine vision, both the source and placement of lighting are extremely important. Light sources include incandescent (tungsten or halogen), fluorescent tubes, strobe lights, lasers, and fiber-optics. Some systems also use infrared or X-ray tubes to detect internal flaws. As in optical microscopy, placement is also a critical factor. Techniques include front lighting, back lighting, side lighting, direct overhead, structured lighting, and ring lighting. The technique chosen is highly dependent on the surface of the object to be inspected and the extent to which it is reflective.

4.3.2.2 Computational Aspect of Imaging Systems

The computational aspect of a machine vision system is concerned with the processing, analysis, and interpretation of the image.

The purpose of the preprocessing stage is to minimize the background "noise" and to enhance and filter the image. There are several techniques used to achieve this. In most commercial systems, the next step after image acquisition is to convert the analog signal to digital. However, some systems in the R&D stage are using optical computing to preprocess the optical signal before conversion by the camera to analog signals. This is done primarily through the use of lenses. Techniques commonly used to preprocess the digital signal include frame averaging, point transformation, histogram equalization and spatial filtering techniques such as neighboring and thresholding or binary-edge mapping.

Many vision systems will also incorporate a data compression or segmentation technique for data handling. Computers, generally, analyze data at a much slower rate than cameras generate data. This is especially important in vision systems that use multiple cameras or color cameras.

A data compression algorithm seeks to reduce the amount of data stored with minimal distortion of the image to be analyzed. The underlying premise is that the data are highly redundant, for example, a base substrate. Segmentation includes windowing, run-length encoding, and area encoding. In windowing, a defined area is analyzed independent of its surroundings. In circuit inspection you could have a global window to include the entire substrate, divide the circuit into small areas, or window certain features. The advantage is that variation in contrast across the circuit can be better dealt with or different algorithms for analysis could be applied to different features.

Run-length encoding compresses data by storing only edge information. Area encoding extends this to two dimensions.

Grey-scale and color refer to how an image is represented within the computer. Most vision systems used in microelectronic assembly use grey-scale image analysis. In grey-scale or monochrome image analysis, the image data is stored in a two-dimensional matrix with integer values called a frame buffer. Each address in the matrix or array is a pixel. Grey-scale systems deal with relative intensity levels per pixel. Typically, systems use 8 or 16 bits of grey level corresponding to 256 or 65,536 shades of grey. Array sizes also vary, with 256 x 256 pixels being common. Arrays are available as large as 4096 x 4096 pixels. The advantage of a large array is greater resolution. The disadvantages are the large amount of memory required and the processing time.

The biggest advantage of grey-scale image analysis is that it can be used in a wide variety of illumination. Recognition is related to the changes in reflectance at the edges, rather than general surface reflection. This permits such things as feature identification and line recognition.

The other technique being considered for vision systems in microelectronics is color.

In color image analysis, the data required is a three-dimensional matrix with integer values. At image acquisition, three different video signals are generated--one in red, one in green, and one in blue. The signals are stored as a grey level intensity in three separate images. For example, 256 grey levels would store 256 levels of intensity for the red signal, 256 levels of intensity for the green signal, and so on. Therefore, three times more memory are required for each image.

Color systems do have a distinct advantage for recognizing color-coded parts, fiducials, and components in which the material has been doped with a colored material. The limitations of present color systems include variation in circuits, lighting problems with brightness of the image, and the trade-off between resolution, memory, and image acquisition time.

Whether color or grey-scale systems predominate may be dictated by material trends. Many feel that color would be very useful in distinguishing materials that are contrast problems, such as palladium/silver, gold, and aluminum nitride. Also, multilayer ceramics and finer geometries may be an impacting factor.

Automated machine vision systems approach image understanding through template matching, image pattern recognition or artificial intelligence. Template matching is a relatively simple two-dimensional form of pattern recognition. Sometimes referred to as subimage matching or "golden board", these systems learn a perfect design from either looking at a physical standard or from a program. A point-by-point intensity comparison is then made. The presence of noise is a major factor in template matching. Techniques for dealing with the noise include cross correlation computation and matched filtering. In practice, template matching systems pass only what is recognized as a match and reject everything else. These systems are sensitive to distortions in grey-scale and geometry.

In pattern recognition, objects within an image are depicted as a set of numbers, each representing the value of a global or invariant to perspective feature. Values are calculated for the characteristic feature and assigned to a known class of similar objects. "In general, a pattern recognition algorithm consists of three steps--segmentation, feature extraction, and classification."[5]

Segmentation is done on the basis of intensity, color or spectral signal and can be pixel-based or region-based. The most common technique is global thresholding, which is pixel-based. Other techniques include adaptive and gradient thresholding. There are several algorithms using the more advanced techniques of region-growing. A popular extension of these are split-and-merge algorithms.[6] Another advanced technique is "pyramid" segmentation which uses pixel linking to achieve low resolution local patterns.

The feature extraction step in pattern recognition is algorithmic and calculates global features of outlined objects. Edges, lines, and curves are features of particular importance. Edge detection processes are a key area for pattern recognition research.

Classification uses global features to match objects with the image model. Assignment of an object to a particular classification is done through a classifier criteria or decision rule. There are two approaches--statistical and deterministic. The statistical approach strives to minimize the probability of misclassification. The deterministic approach "assigns an unknown object to the class of the closest known object."[5]

Scene analysis is a different approach to pattern recognition. It is also referred to as structural pattern recognition or syntatic pattern recognition. In it, an object or scene is defined as a set of primitive subpatterns. The features of those primitives are used to identify allowable structures and allowable relationships between them. Each facet of scene analysis is highly integrated. Scene analysis also involves segmentation into

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[5] Chen, 1985.

[6] Pavlidis, 1974.

morphs which are specific shapes. The next facet is object description which can be geometric, symbolic or a combination of both. Industrial vision systems usually use geometric object characterization. The actual interpretation is done through algorithms that recognize the occurrence of structures within derived relationships.[7] Techniques for interpretation include geometric transformation, graph matching, and relaxation labeling. Relaxation labeling is interesting because it applies to both geometric and symbolic object descriptions. It is a deterministic approach.

Pattern recognition is limited by the contrast and complexity of the object being imaged. Thresholding for segmentation is particularly affected by lighting. Feature selection is a major problem. In most systems, the choice of which features to extract for definition and identification is somewhat arbitrary. The number of features required is also an issue. This is especially relevant in decision-rule classification. The process is iterative and some information is discarded at each decision stage. Therefore, there is a tradeoff between the number of features extracted and an acceptable error rate.

Image processing systems for machine vision are also trying to make use of artificial intelligence, particularly expert systems. An expert system consists of a knowledge base of facts and heuristics, an inference procedure, and a working memory or global data base.[8] It should be noted that heuristic searching does not always result in the best solution, but rather one that is "good enough" within its limitations. Hence, a major application is in handling uncertain cases. Also, expert systems are highly dependent on the knowledge base. Establishing expert criteria can be a significant problem for some inspection tasks.

Computer architecture is another important consideration in image processing. Conventional computers analyze data sequentially. In order to manage very large amounts of data and in less time, image processing systems are utilizing parallel processing. The common approaches to parallel architecture

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[7] Nandhakumar and Aggarwal, 1985.

[8] Gevarter, 1984.

are bus-structured systems, pipelined systems, cascaded pipeline systems, processor arrays, and systolic arrays. Computer architecture is a major focus of current research and development for image processing with emphasis on pipelining and the use of systolic arrays.

In pipelined systems, an operation is divided into smaller suboperations which are performed simultaneously on different elements of data.[9] Systolic arrays pipeline data through small arrays. It allows the multiple use of each element of input data, resulting in a simpler system, higher throughput, and lower communication costs.

4.3.3 Two-Dimensional Machine Vision Systems

Most two-dimensional vision systems developed for inspection in microelectronic manufacturing were developed for printed circuit board inspection. Their primary applications are for paste inspection, solder and orientation inspection, and part verification. The facet of hybrid circuit assembly where two-dimensional inspection would be applicable is the substrate stage.

Limitations of existing systems include:

- false defect rate
- detecting markings
- reading markings
- slow throughput
- inability to keep pace with automatic printers
- contrast.

Companies prominent in two-dimensional and X-ray based machine vision for microelectronic inspection include the following:

A.O.I. Systems, Inc.
Lowell, MA

Centaure Vision
Irvine, CA

Cognex Corp.
Needham, MA

DIT-MCO, International Corp.
Kansas City, MO

[9] Delo and Friedman, 1984.

Everett/Charles Test Equipment
Pomona, CA

Gerber Scientific Inc.
South Windsor, CT

IRI (International Robomation Intelligence)
Carlsbad, CA

IRT Corp.
San Diego, CA

KLA Instrument Corporation
San Jose, CA

Lincoln Laser
Phoenix, AZ

Mnemonics, Inc.
Mt. Laurel, NJ

Oprotech, Inc.
Billerica, MA

Orbot, Inc.
Woburn, MA

Photonic Automation
Santa Ana, CA

R.V.S.I. (Robotic Vision Systems Inc.)
Hauppauge, NY

Synthetic Vision Systems
Ann Arbor, MI

Universal Instruments Corp.
Binghamton, NY

Vanzetti Systems, Inc.
Stoughton, MA

View Engineering
Simi Valley, CA

Westinghouse Vision Systems
Columbia, MD

4.3.4 Three-Dimensional Machine Vision

Three-dimensional systems represent both the greatest challenge to automating hybrid inspection and the greatest opportunity. Three-dimensionality is necessary for inspecting component and die attachment, wire bonds, and precap. Inherently, there are several features of hybrid circuits which require at least detection and assessment of height and, in some cases, measurement of height, as well as length and width. This is especially important for wire bond inspection, but also for determining such things as the depth and quantity of fillet and depth perception of cracks and voids. Most people feel three-dimensional automated inspection will become even more important as the use of surface mount increases for printed circuit board production. The primary reason being the increased number of layers in surface mount boards.

Three-dimensional imaging can be achieved by use of dual cameras to create a stereo image, optical ranging, and triangulation or structured light. A dual-camera system takes a right and left image or "picture" and merges them into a single image by measuring the apparent displacement between the object and the two cameras. This is also referred to as disparity stereo and is a form of passive triangulation. There are two major problems associated with this. One is that the hardware lacks the resolution and accuracy needed for hybrid circuit inspection. Nonoverlapping areas and occlusion may cause missing points. The second problem is software related. Even with parallel processing, the time required to form the single image and, further, to then identify the object is not prudent for microelectronic inspection applications.

Optical ranging is based on the principle of time-of-flight measurement. These types of systems also include both pulsed and continuous-wave laser radar. In a time-of-flight system, a signal carrier, such as acoustic or optical wave is sent from the measuring system, reflected off the object, and returned. Since the velocity of the signal is known, the distance can be determined by measuring the time required for the signal to travel. Typically, the signal will be sent and returned along the same path, further simplifying the measurement and avoiding the problem of missing points that is inherent to triangulation. Three-dimensionality is achieved by scanning the entire scene. In general, time-of-flight systems are not easily scaled to different measurement ranges. Other problems with optical ranging include low resolution, the time required to construct an image, and difficulties associated with measuring the beam's transit time which is in the picosecond range. In practice, a longer distance is usually put between the systems and the object in order to increase the transit time to a measurable value. However, this lowers the resolution and, overall, makes the technique impractical for hybrid inspection.

Continuous-wave laser radar differs slightly in that the distance the signal travels is determined by measuring the phase shift in the return signal and an amplitude detector can be incorporated to measure intensity. Here there are the problems of power required, signal-to-noise ratio, resolution, and processing time.

Most three-dimensional systems being developed today involve structured illumination and are based on the geometric principle of triangulation. These are also sometimes referred to as active geometric techniques.

There are basically five approaches to applying active triangulation. These are:

- Point-by-point
- Line-by-line
- Grid projection
- Coded grid projection
- Moire interferometry

Companies most active in development of three-dimensional machine vision systems for inspection of microelectronics include:

- CyberOptics
- Gould
- IRI (International Robomation Intelligence)
- Lincoln Laser
- Photonic Automation
- Robotic Vision Systems
- Synthetic Vision Systems

<u>CyberOptics Corporation</u>
2331 University Avenue SE
Minneapolis, MN 55414

Contact: Steven Case
(612)331-5702

CyberOptics Corporation produces laser based, noncontact sensors for hybrid circuit inspection. They combine their sensors with computer controlled translation stages to build 2-D cross-sectional measurement instruments and full 3-D viewing instruments. Built-in data processing algorithms compute heights, lengths, cross-sectional areas, solder paste volume and other attributes. The systems benefit users by allowing nondestructive, noncontact measurements on solder paste, reflowed solder, wet or fired resistors, Tape Automated Bonding (TAB) leads and lead co-planarity. Figures 1-4 show various 3-D and 2-D measurements of importance to hybrid circuit production.

CyberOptics figures

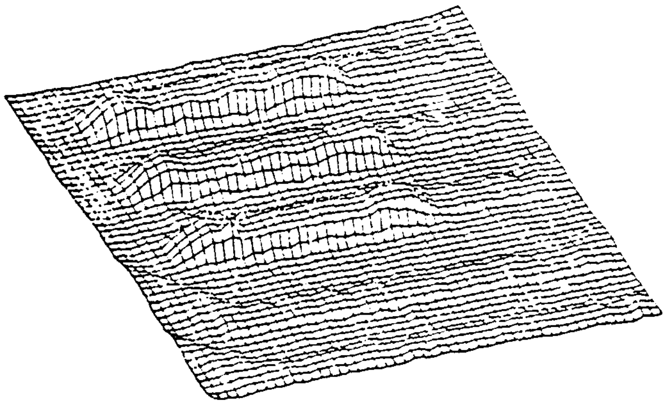

Figure 1. 3-Image of Solder Paste Screened onto 3 Circuit Pads.

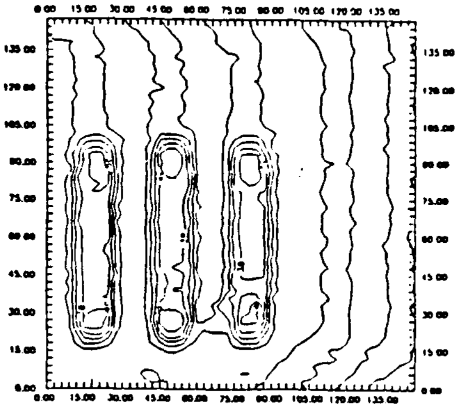

Figure 2. Contour Map of the Solder Paste in Figure 1. Height Contour Intervals are 2 mils. Raised Circuit Traces are also Visible.

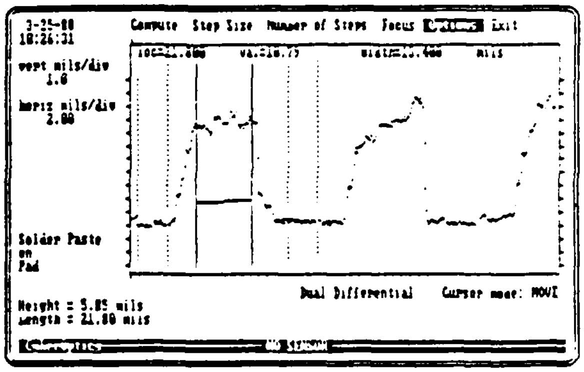

Figure 3. Height Measurement from Solder Paste Profile.

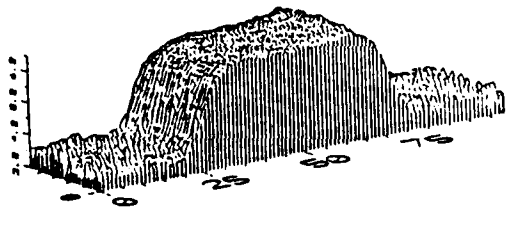

Figure 4. 3-D Image of Wet Thick Resistor. The Resistor is Approximately 2 Mils Thick.

Gould, Inc.
NavCom Systems Division
El Monte, CA

Contact: Albert Lee
U.S. Army Laboratory Com.
Harry Diamond Laboratories
(205)394-2840

Under a contract for the U.S. Army, Harry Diamond Laboratories, Gould is developing a 3-D system for wire bond inspection. The illumination source is a dual-element light ring utilizing two fiber optic bundles. The angle of lighting is structured through a computer-controlled shutter. Computation is a combination of design rules and artificial intelligence written in C language. The system looks at ten defects: shorted and broken wires, wire separation, wire track, ball or wedge location with respect to the pad, missing die or wires, and debris. At present the system is in prototype and is looking at 6 components and 35 wire terminations. There is a hard copy output of defects and where they are located. If the number of defects is excessive, the machine defaults and terminates inspection.

IRI - International Robomation Intelligence
2281 Las Palma Drive
Carlsbad, CA 92009

Contact: Don Mead
(619)438-4424
(ext 224)

IRI produces vision systems for a variety of applications including robot guidance, sorting, product identification, and quality control inspection of film, ink cartridges, and particularly printed circuit boards. They have also produced systems for inspection of wire bonds and solder paste. Since 1982, they have installed over 1200 general purpose vision computers. Their 2-D systems use data direct from CAD.

Their approach to 3-D is to use multiple-angled area cameras with a strobed light source. They have a 3-D system for inspecting wire bonds on hybrid circuits. The system looks for bent or lifted wires, the presence or absence of components, the bond pad, loop trajectory, and accuracy of epoxy and paste placement. An important aspect of the system is windowing and feature detection. The system takes advantage of the high spatial frequency associated with wire bonds.

Lincoln Laser Co.
234 East Nohave
Phoenix, AZ 85004

Contact: Dan Driscoll
(602)257-0407

This company makes 2-D systems for printed circuit board inspection and have made systems for substrate inspection. At present they are not working on 3-D. They are included in this group because they have made a 3-D system in the past. However, it is not presently in use.

Their systems use laser, line-scan cameras. Resolution is spot-size dependent. Lincoln Laser designs to the component level. The company feels its strength is in their image acquisition capability and, especially, optics.

The computational aspect uses design algorithms in conjunction with feature recognition from CAD or a golden-board.

Photonic Automation, Inc.
3633 W. MacArthur Blvd.
Santa Ana, CA 92704

Contact: Joe Donahue
(714)546-6651

They are developing a 3-D system which uses a laser source and is window-based. The system scans at video rates and has 1 mil resolution in the x, y, and z directions. The system uses pipeline architecture and analysis and interpretation is a combination of design rules and pattern recognition. The primary application is for pre-reflow solder inspection.

They are currently working on a new product which they anticipate to be available in 1989. The system which is currently at a laboratory demonstration stage uses a laser light source and will have 0.1 mil resolution. The unique aspect of the system is the detection technique.

RVSI - Robotic Vision Systems, Inc.
425 Rabro Dr.
Hauppauge, NY 11788

Contact: Howard Stearn
(516)273-9700

Currently, RVSI is focusing 3-D development efforts on a system for inspecting solder joints on printed circuit boards. The system is based on triangulation and structured light. Image acquisition uses a proprietary laser-based sensor system. The computation aspect uses a rule-based system and is programmed in C language. They consider it an expert system designed to emulate present-day military specifiation inspection criteria.

The advantages of such a system are consistent inspection criteria, reduced rework, data archiving, automatic storage, and automatic process feedback. It is anticipated that initially the system will match or exceed human speed.

<u>Synthetic Vision Systems</u>
3744 Plaza Drive
Ann Arbor, MI 48108

Contact: David Trail
(313)665-1850

They produce a 3-D laser scan system based on the triangulation concept. The system is capable of doing loop height verification and bond inspection. It is felt that it could be applied to Pre-Cap as well. Resolution is 0.5 mil (0.0005 in.) in the z direction. The system is unique in that it calculates an entire field-of-view or one megabyte of data and uses proprietary sensing electronics. Synthetic Vision has developed a special lateral effect photo diode which they have incorporated into their system.

5.0 TRENDS AND AREAS OF DEVELOPMENT

5.1 HYBRID PRODUCTS AND PRODUCTION

The demand for hybrids is increasing, but the type of products are shifting. One major trend will be the increased use of power devices and hybrids for high-frequency applications. Another is greater production of digital hybrid circuits over analog. The primary result of these and other trends is that hybrids are getting denser and more complex. Although substrates are getting bigger, which is a problem for inspection itself, the number of components per square inch is increasing also as are the number of wires. As circuits become more complex, assembly errors are more likely to occur. Also, smeared metallization becomes a greater problem.

In the commercial sector, the product trends are away from the use of precious metals and an increased usage of Teflon as a substrate. Custom and military-grade circuits could be affected if silicon is used as a substrate material. Contrast would be a serious problem.

Other product trends include multilayer ceramics, finer geometries, and greater use of solder over eutectic bonding.

In production of hybrids, the major trend is to faster production runs and the increased use of automated production equipment. However, assembly and inspection are not automating at the same pace, creating bottlenecks in production. Also, with automated production, there is an increased potential for damage. Handling is faster, machine wear is a consideration, and because production is faster than inspection, many bad circuits could be produced before a problem is identified. Automation requires much stricter process control.

5.2 VISION SYSTEMS

In optical microscope systems, developments appear limited to incremental improvements. These include motor-driven focus, automatic defect marking, display monitors, viewing ports, and improved lenses. Another technique being explored is the use of headphones on the operators to communicate where defects are located or if there is a consistent problem.

The major focus of development is image acquisition and illumination. High-resolution cameras and particularly the sensors are the key areas of interest. In many systems, the sensors are highly proprietary and represent the competitive advantage of a system. Structured lighting is a prominent research area because of its importance to achieving three-dimensionality. Other techniques include fiber-optics, ultraviolet lighting, and holography. Holography is an area of great interest, but it is not generally perceived as being applicable in the near future.

The computational aspect of vision systems is also an area where improvements can be foreseen. Most present vision systems use one of the few vision algorithms from the last decade. However, there is a great deal of development effort in vision algorithms, particularly for the feature extraction stage. Prominent organizations in this field include: Purdue University, University of Maryland, M.I.T., S.R.I., Carnegie-Mellon, and N.B.S.

One approach uses artificial intelligence through what is called knowledge based image analysis. This is similar to scene analysis in combination with expert systems and embodies decision rules and adoptive algorithms for the feature extraction and classification steps.

6. SUMMARY OF FINDINGS

6.1 USE OF NEW TECHNOLOGY

Most major producers of hybrid circuits have considered automated inspection and many have tried to implement it. The hybrid industry is somewhat unique in its willingness to adapt new technology. In most industries there is a reluctance to be first to use a new process or equipment, but this does not appear in the hybrid industry.

6.2 ADVANTAGES/LIMITATIONS OF EXISTING MACHINE VISION SYSTEMS

There are several limitations and criticisms of existing machine vision systems for inspecting hybrid microelectronics.

6.2.1 Sensitivity

Sensitivity of machine vision systems is a major problem. Many companies said they could not reach a compromise between false alarms and false pass. This is especially evident in comparitor systems. These systems look only at what is good or programmed in the system as good and reject everything else. For example, a piece of lint could be considered a defect, but a cut in a line would pass as good.

6.2.2 Template Matching

Another problem with many comparitor systems is that they require a "golden board" to form the template for comparison. Making a perfect part is time-consuming and it is sometimes difficult to establish what is perfect.

6.2.3 Setup Time

Setup time is another serious concern with vision systems. A hybrid producer typically has 500 active designs that utilize combinations of hundreds of parts. Each time a different part is used in production, it must be taught to the machine. However, most manufacturers doing a significant production of hybrids use computer-aided design. The ability of a vision inspection system to accept a pattern directly from CAD is a tremendous advantage.

6.2.4 Throughput

Speed or throughput rate is another impediment to the use of machine vision inspection systems. Generally, machine vision systems applied to hybrids are thought to be too slow. Many systems step and repeat the image in small sections which takes a lot of time. To some extent, throughput rate is a trade-off with cost. Increasing throughput requires greater computational capacity and faster scan rates. One producer of vision systems estimates a ten percent increase in throughput could double the price of a machine. In a sense, automation represents an antithesis for hybrid inspection. Automated production creates a greater need for automated inspection as an integral part of the assembly process. However, present inspection systems cannot keep pace with automated processes such as substrate screening.

6.3 CHALLENGES AND SOLUTIONS TO ADVANCING THE STATE-OF-THE-ART

Opinion varies as to what is the greatest obstacle to better machine vision systems. It is difficult to segregate one single aspect.

6.3.1 Optical Discernment

Optical discernment is often cited. The problem here is that most vision systems have a fixed focus, but the heights of parts across a circuit varies. In order to obtain enough resolution, the working distance must be very close; however, this limits the depth perception. A human operator can change focus, magnifications, or even physically move the circuit to better discern details. Approaches to overcome this problem in machines include multiple cameras at varied magnification levels and cameras that go in and out of focus. Both of these approaches are very slow and throughput is already a problem.

6.3.2 Signal Processing

Signal processing is another aspect of machine vision where people perceive there to be major barriers to advancing the state-of-the-art. As discussed previously, the three areas of developmental interest are preprocessing, pattern recognition algorithms, and hardware. Preprocessing is a primary focus of development with the field of optical computing representing a significant promise of improving image analysis. In pattern recognition algorithms, a great deal of effort is in applying artificial intelligence to image interpretation. Hardware developments continue to concentrate on architecture and the implementation of faster chips.

6.4 OPTIMAL STAGE TO AUTOMATE INSPECTION

In considering at what stage in the assembly process automated inspection would be the most useful, opinion varies widely. Strong arguments can be made for each stage; however, the greatest interest seems to be at the pre-cap stage.

6.4.1 Incoming Components

The need for automated inspection at incoming components seems to be at two extremes. Either a company has no problem with it at all, or it is a significant issue. The determining factors appear to be organizational structure and customer/supplier relationships.

As discussed in Section 4.1, inspection of incoming components is done by separate personnel from assembly inspection and, in some organizations, under separate management. This raises a key issue and that is establishing criteria for an incoming component inspection protocol. The problem is exacerbated by the large number of parts used, the variety of the same parts because of multiple suppliers, the time between parts received and actual circuit production, and automated pick-and-place machines.

Inspection of incoming components is usually done on a sample basis. A defective or incorrect part may not be realized for weeks or even well into the production process. Hence, the rationale that this is the least expensive point to catch a defect before any labor has been added or rework is required.

Supplier relationships and sourcing is another key issue. Often availability of components is critical and a hybrid producer is forced to use less quality conscious suppliers and screen out what is bad.

Chips, however, are not as serious a concern. These are usually 100 percent inspected or major producers will often have their own inspectors on site at the vendors. Integrated producers who are supplied through their own company usually have an advantage.

6.4.2 Component and Die Placement and Attachment

Automated inspection of component and die placement and attachment appears to be of greatest interest to thin-film hybrid producers. This is because of the nature of the process and the two-time rework limitation associated with Class S hybrids.

6.4.3 Pre-Cap

The argument for or against pre-cap as the priority for automating inspection is an economic issue. One school of thought is that it is too late in the process for identifying defects, because all of the value-added is already in the device. The other more widely held opinion is that pre-cap would be the most useful stage to automate because it is the most labor-intensive, requires the most time, is the most complex due to the multiplicity of components, and is required by military specifications. Also, it is felt that automating pre-cap inspection would minimize contamination.

The issues are: What is the cost of pre-cap inspection in relation to the overall material and processing costs; and is the time required for pre-cap inspection a burden on production flow? For example, in a \$200 hybrid, pre-cap inspection might represent 2 percent of the cost. In a \$1,000 device, that cost would be less than 0.5 percent. Another approach is to consider what percent of devices are found to be defective at pre-cap. If the percent of devices passing is very high, inspection is more costly and time-consuming, favoring automated pre-cap inspection. If the percentage of defects is high, there is a greater argument for more intense in-process inspection.

6.5 MACHINE VISION VERSUS OPTICAL MICROSCOPY

The issue then arises: Why use a vision system over human operators at all?

6.5.1 Economics

On a purely economic basis, automated vision systems for hybrid microelectronic circuit inspection are difficult to justify. Salaries of assembly inspectors are typically in the \$10 to \$14 per hour range, including salary-related costs. A stereomicroscope station with accessories can typically be purchased for less than \$5,000. Optical microscopes also provide flexibility. An operator and microscope can be added or removed from a line at a relatively low incremental cost. Although it would be unlikely, microscopes can be used for other purposes or re-allocated to another department if no longer being used for hybrid production.

Automated vision systems are a substantial capital investment. There is not only the initial cost but energy usage, maintenance and service to consider. Setup time and programming costs may also be applicable. Annual service contracts on capital equipment are usually 10 pecent of the initial cost of the equipment.

6.5.2 Subjectivity

In the decision between using human inspectors and automated vision systems, there are other factors to consider. Automated vision systems have certain distinct advantages that are not easily quantified. Foremost, is the potential to eliminate or at least to reduce the ambiguity associated with human operators. The rationale is that the machine will apply the same criteria each time it inspects. At present, inspection is very subjective and highly operator-dependent. One problem that now occurs is that an operator may identify a particular defect and pass everything else on the circuit. After rework, that circuit may be inspected by another person who sees something different as defective which was passed by the first inspector and the circuit must be reworked again. This could be eliminated with machine vision inspection.

6.5.3 Information Management

Another important consideration in using automated vision systems is the opportunity to improve information management. Since the information is already in a digital format, it can easily be archived for future reference, analyzed for optimizing process control, or incorporated to directly feedback to rework or a production station.

6.5.4 Use of Facilities

Another less obvious advantage may be use of production floor space. It is most likely that an automated machine vision system would require less production floor space than numerous human operator stations, representing an opportunity for cost savings.

6.6 THE HYBRID INDUSTRY AS AN OPPORTUNITY FOR MACHINE VISION PRODUCERS

The next question that arises is: What opportunity does the hybrid business represent to a machine vision system producer? The three-dimensional machine vision industry is comprised primarily of small, entrepreneurial companies. Since they have limited resources and capital, market potential is a major factor. Whereas a major corporation could have other motivations for developing an instrument, such as a competitive process advantage.

The general consensus among both hybrid circuit and vision system producers is that, at a price of $100,000 or more, the market for automated vision systems for hybrid microelectronic circuit inspection is fifteen machines. Larger markets for vision systems would be for solder joint inspection or printed circuit boards and wafer inspection, especially of VLSI dies. On the other hand, these may also be a greater technological challenge than hybrid circuit inspection. It is anticipated that the technical developments in optics, image acquisition, and signal processing that would be incorporated into a hybrid inspection system could be further developed to serve products in the larger markets.

Standardization is another prominent issue in the hybrid circuit industry. Hybrid microelectronic circuits are designed based on form, fit, and function. Some advocate greater standardization of design which could facilitate automated processing and inspection; for example, a set orientation of a certain type of component. However, greater standardization invites greater competition, particularly from offshore producers. The unique position of the U.S. custom hybrid business is largely due to the close relationships between hybrid circuit producers, users, and the customized nature of the product.

6.7 IMPLICATIONS OF AUTOMATING INSPECTION

The final issue to consider is the implications of automating inspection to the U.S. hybrid circuit industry. The premise is that automation would ultimately improve quality and lower cost or at least maintain a competitive cost. The structure of the U.S. hybrid circuit industry can be viewed as follows:

Major Independent

Medium-Sized Producers

Major Captive Producers

Captive Producers

Small Producers

Companies investing in automated equipment would be in the major independent and major captive categories Nearly every large company involved in electronics use and production has the capability to make hybrid circuits. The question then becomes a make-or-buy decision. Companies which are not major captive producers maintain in-house hybrid production in order to service other divisions, protect a proprietary design, or utilize existing equipment and engineerig capability. In many cases, producing hybrid circuits is an incremental cost. These types of producers are unlikely to invest in automated inspection. However, if automated inspection significantly advances the state-of-the-art in production of hybrid circuits, this could influence the make-or-buy decision of captive producers to use outside suppliers.

Also, the hybrid microelectronic circuit industry is unique in that the dominant producers vary from year-to-year based on end-use product markets, such as cellular telephones, disk drives, the demand for a particular model of an airplane, or a particular military weapon system. This fluctuation in production levels does not favor automation investment. However, automated inspection, if broad enough in its application, could stimulate greater production by independent companies to meet those products' specific demands.

As in the printed circuit board industry, the successful implementation of automated inspection would most likely result in a shakeout of undercapitalized small- to medium-size producers, with certain small, specialized "niche" producers always maintaining a presence. However, this is being foreseen to some extent regardless, due to material changes, product complexity, and increasing competitive pressures, particularly as offshore producers focus more on the custom segment of the business.

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STATE-OF-THE-ART REVIEW | Date: June 1988

VISION TECHNOLOGY FOR AUTOMATED INSPECTION OF HYBRID MICROELECTRONICS ASSEMBLIES

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